LIGO DETECTOR AND OBSERVATION OF GRAVITATIONAL WAVES

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OUTLINE

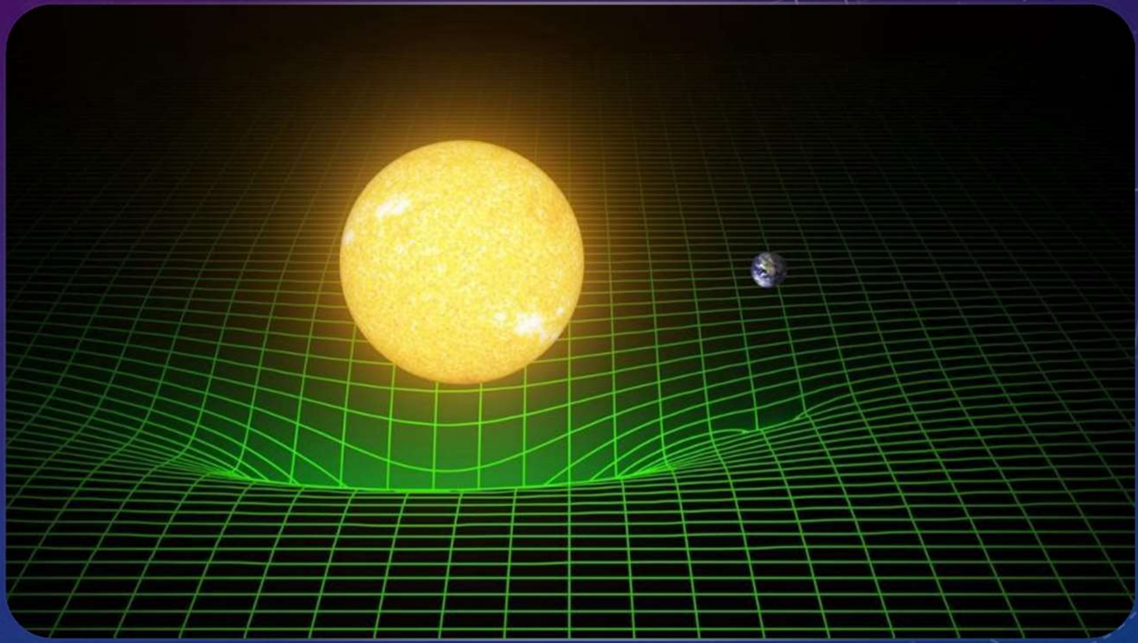
1. Introduction of Gravitational Waves and their Characteristics
2. Historical Background of these Waves
3. Working Principles of LIGO
4. Evolution of LIGO characteristics with time
5. Results obtained by LIGO
6. Analysis of the Results

NEWTON'S THEORY OF GRAVITY (1687)

- Newton's theory defines gravity as a force which gets smaller when the distance gets bigger between the two bodies.
- It helps us in almost all that we need in our daily life.
- But it is wrong, and Einstein saw this quickly after he developed the "Special Theory of Relativity".
- The problems in Newton's theory were that it didn't have a way to deal with massive bodies moving with a very high velocity.
- It also didn't have any way of communicating information in the gravitational field from one place to other.

EINSTEIN'S GENERAL THEORY OF RELATIVITY (1916)

- Einstein's theory claims that gravitational masses distorts spacetime and this distortion in spacetime leads to motion of other masses.
- In this theory there is an existence of gravitational waves through the field.



The warping of spacetime by gravitational masses. Image Credit: LIGO/T. Pyle

GRAVITATIONAL WAVES EINSTEIN 1916 AND 1918

- The sources for these waves are non-spherically symmetric accelerated masses.
- They move with the speed of light.
- They are transverse waves that distort space perpendicular to the direction they move.
- This leads to a constant strain along the wave and this is what was measured in the waves.

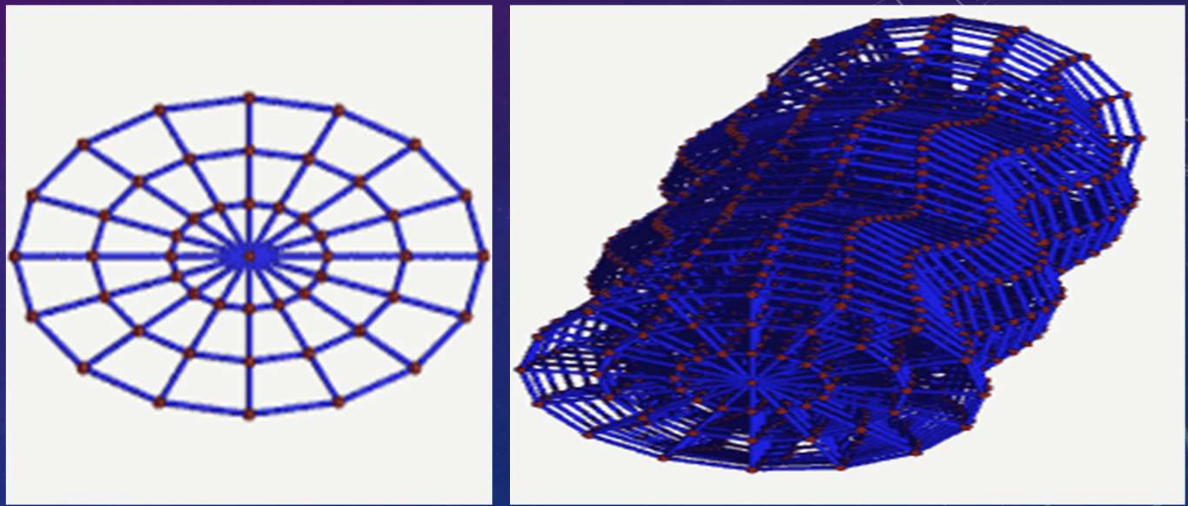
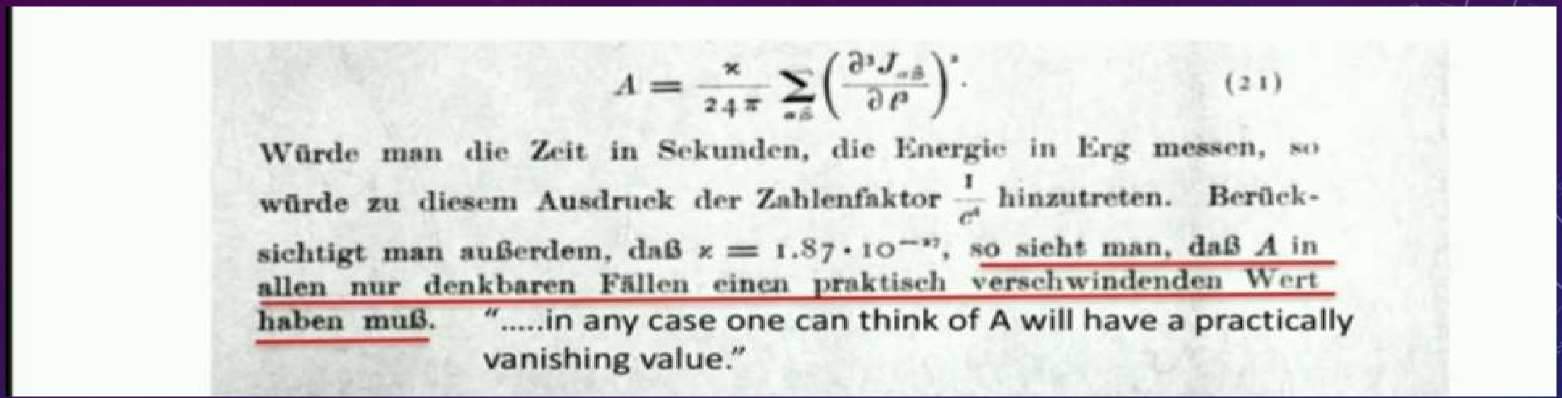


Image Credit: http://www.einstein-online.info/spotlights/gw_waves.html

EINSTEIN 1916



$$A = \frac{\varkappa}{24\pi} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3} \right)^2. \quad (21)$$

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

"…..in any case one can think of A will have a practically vanishing value."

$$h(Strain) = \frac{\varphi(Newtonian)}{c^2}\frac{v^2}{c^2} = \frac{Gm}{Rc^2}\frac{v^2}{c^2}$$

Train Collison

m = 10^5 kg

v = 100 km/hr

T(collison) = 1/3 sec

R(radiation) = 300km

h ~ 10^{-42}

Binary Star Decay

m_1 = m_2 = 1 Solar Mass

T_{orbit} = 1 day

R = 10,000 ly

h ~ 10^{-23} @ $^1/_2$ day period

Decay time ~ 10^{13} years

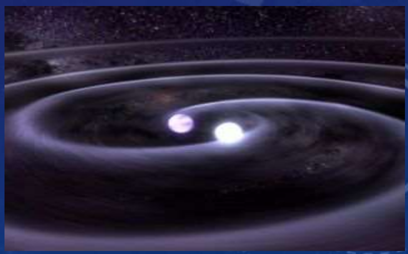


Image Gredit : Google Images

GRAVITATIONAL WAVES EVIDENCE

- Neutron Binary System (Hulse & Taylor)
  - 1913 + 16 -------Timing of the pulsars
  - Separated by 10^6 miles
  - m_1 = 1.4 m_{sun} , m_2 = 1.36 m_{sun} , ε = 0.617
- Predictions from General Relativity:
  - Spiral in by 3mm/orbit
  - Rate of change in orbital period

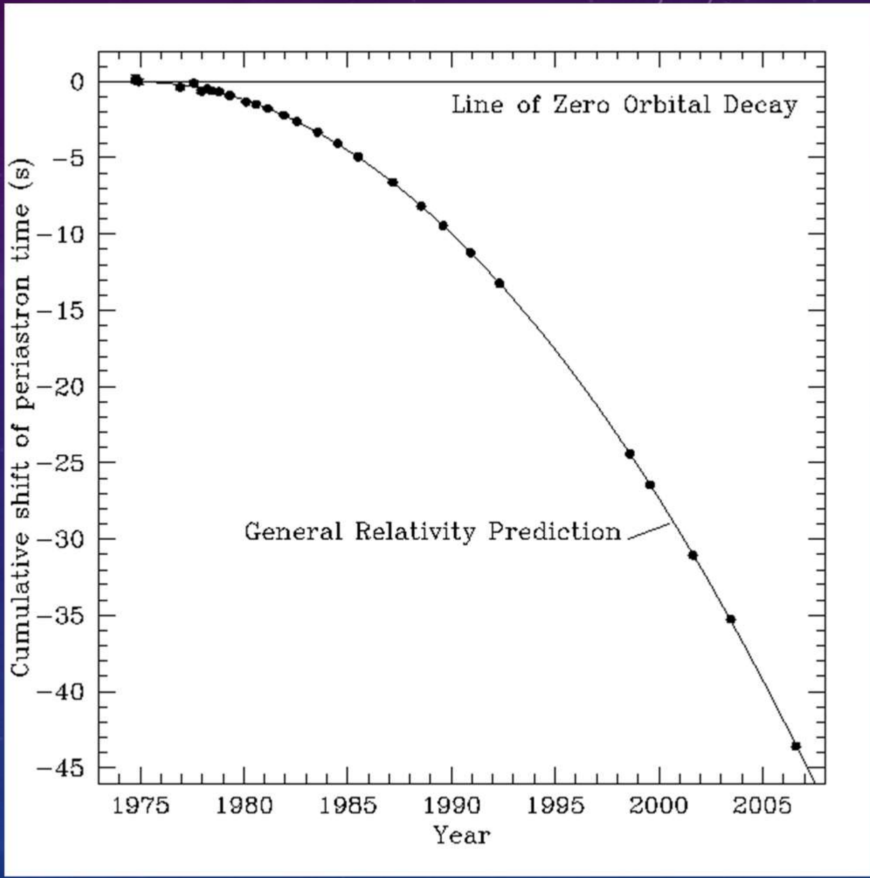
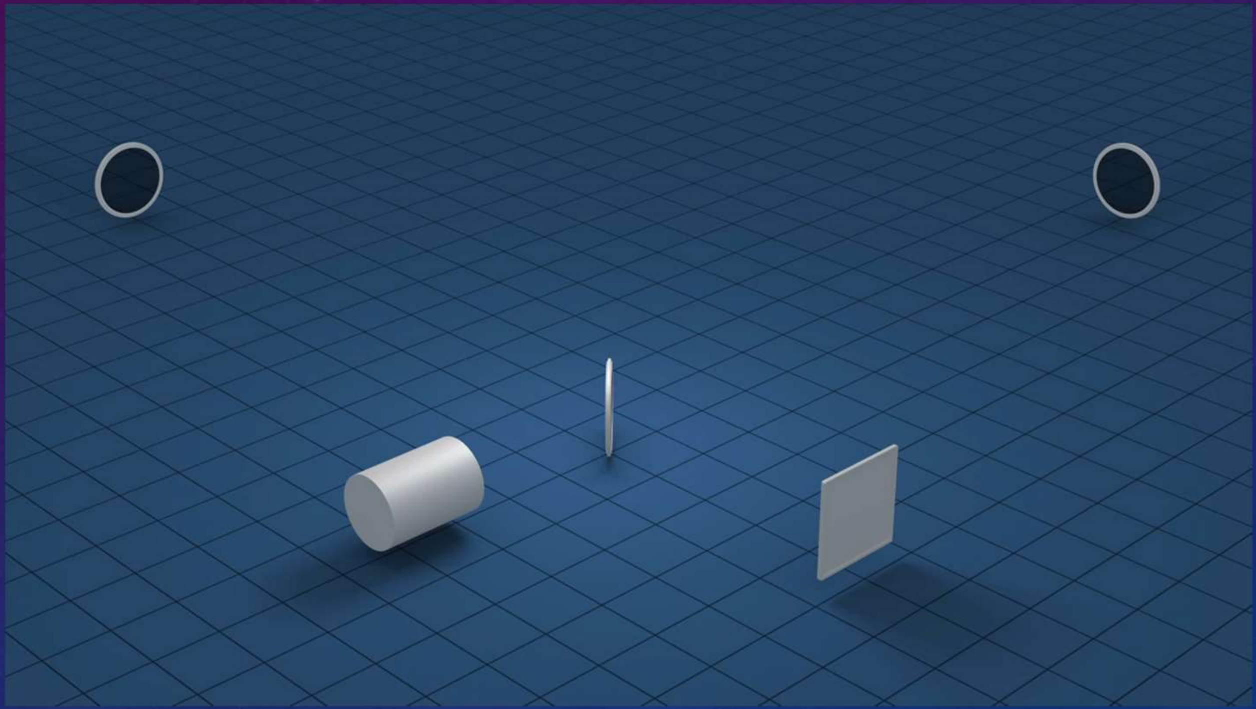


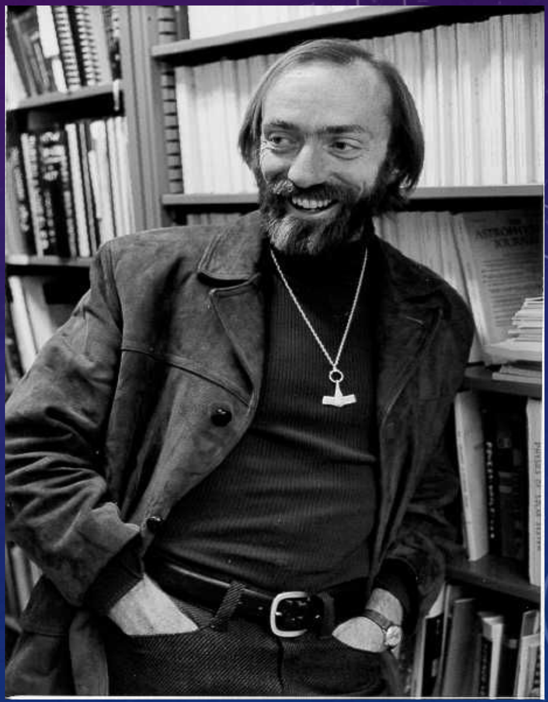
Image Credit : https://astronomy.stackexchange.com/

THE RULER USED FOR MEASUREMENTS



THE MEASUREMENT CHALLENGE

- h = $\frac{\Delta L}{L} \leq 10^{-21}$
- L = 4 km, ΔL ≤ 4 x 10^{-18} m
- ΔL ~ 10^{-1} wavelength of light
- ΔL ~ 10^{-12} vibrations on Earth's surface



Kip Thorne
Image Credit : Google Images

THE LIGO SETUP

The Optical Resonator

- The combination of the input and end test mass comprise an optical resonator (Fabry-Perot cavities).
- It bounces the light between them many times to increase the gravitational wave induced before returning the light to the beam splitter.
- No sidebands return to the laser, but all the carrier does.

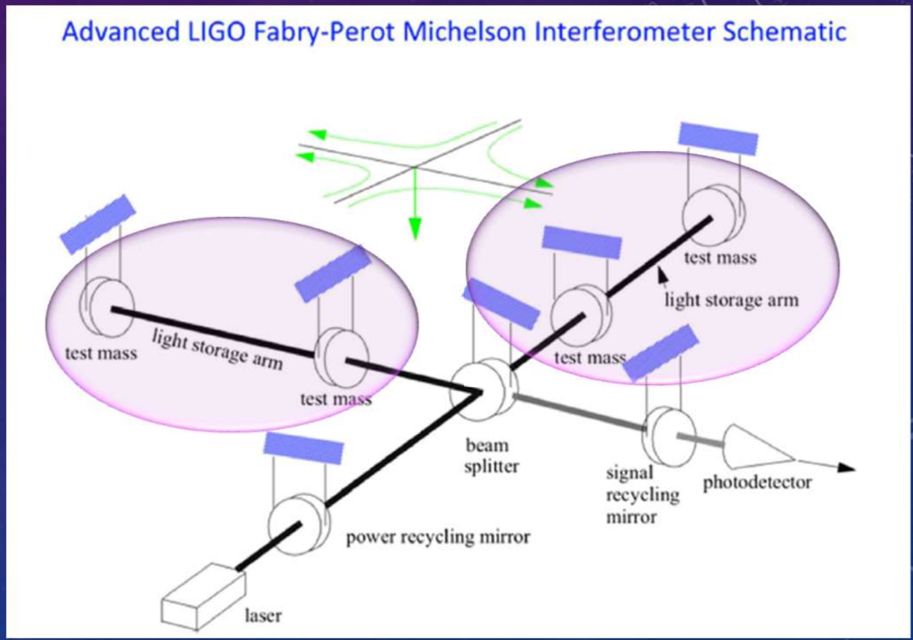


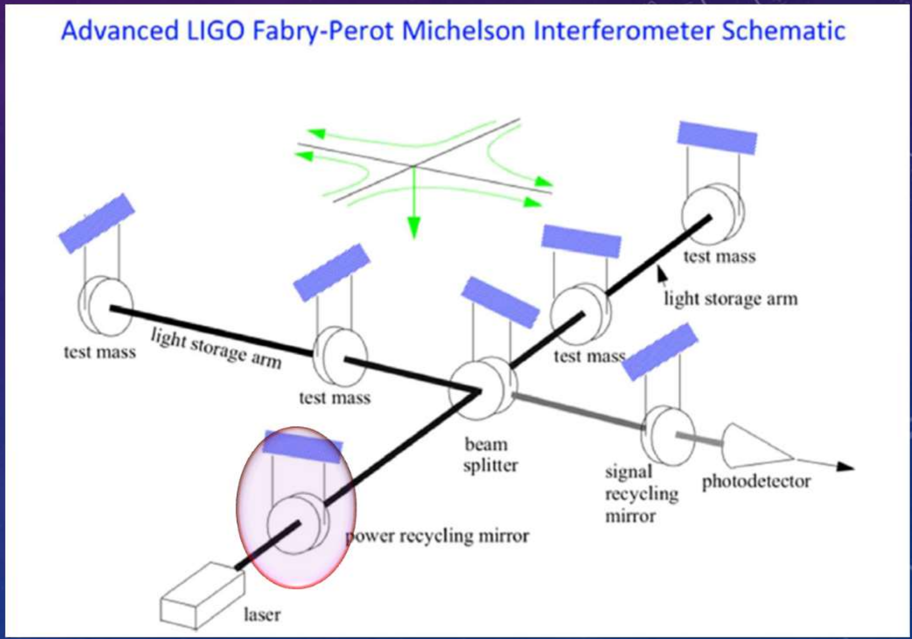
Image Credit : www.ann-phys.org

THE LIGO SETUP

Power Recycling Mirror

- The position of this mirror cancels the carrier reflected by mirror with the carrier transmitted back by the recycling mirror from the beam splitter.

- This eliminates the carrier being reflected by the interferometer to the laser and builds up the carrier power between the beam splitter and the input test masses by several hundred.



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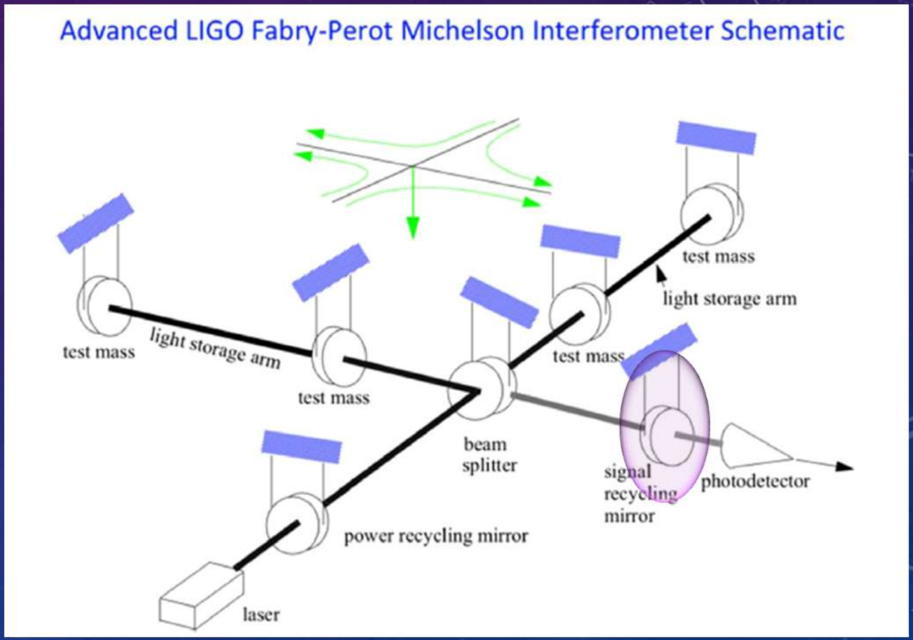
THE LIGO SETUP

Signal Recycling Mirror

- This mirror reflects the sidebands back into the interferometer and modifies the spectral response of the entire interferometer to the sidebands.
- The spectral response of the detector thereby become the gravitational waves.



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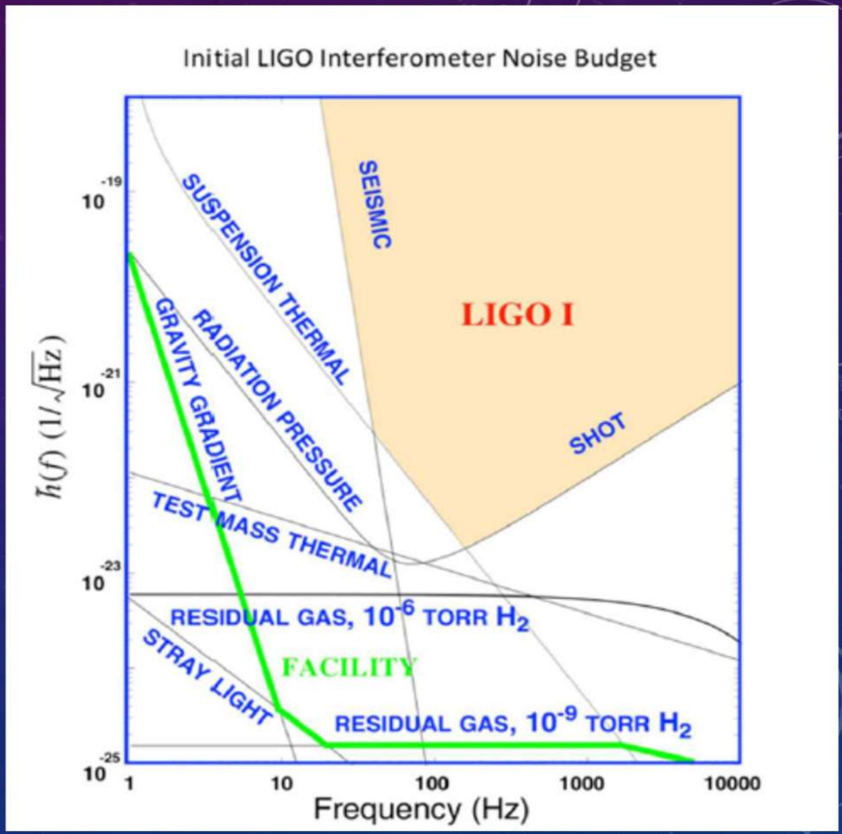
THE NOISE CONSTRAINT

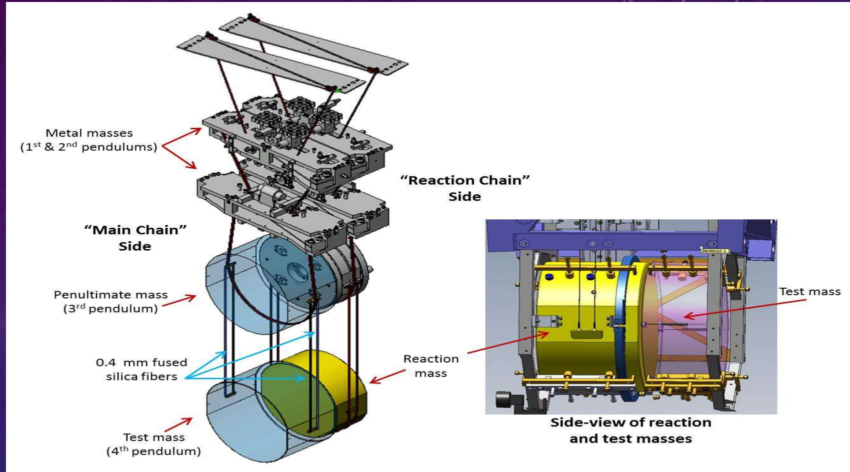
- At frequencies above 200 Hz, the quantum noise limits the performance.
- The noise near 100 Hz is also limited by the thermal noise in the pendulum suspension, in this case phonon excitations at the end points of the pendulum.
- At frequencies below 70 Hz the detector is limited by incomplete removal of the ground vibrations (seismic noise) at the mirror.
- The broad noise spectra called residual gas are the phase fluctuations induced by forward scattering of residual gas molecules.
- Gravity gradients is due to the fluctuating Newtonian gravitational forces on the end test masses caused by time dependent density fluctuations in both the atmosphere and the ground.

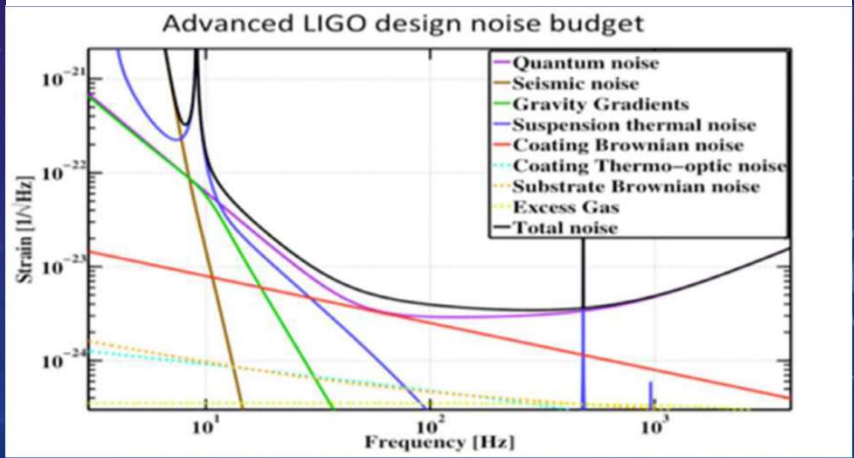


Amplitude Strain vs Frequency
Image Credit : *https://www.ligo.org*

QUAD SUSPENSION

- This setup provides four stages of high frequency ground noise isolation.
- They have a low pendulum thermal noise by using fused silica fiber supports in the final pendulum stage.
- The dominant noise has become the quantum noise at both high and low.
- The noise limiting the performance 100 Hz has become the thermal noise generated in the mirror coatings.





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EVOLVING IMPROVED SENSITIVITY OF LIGO

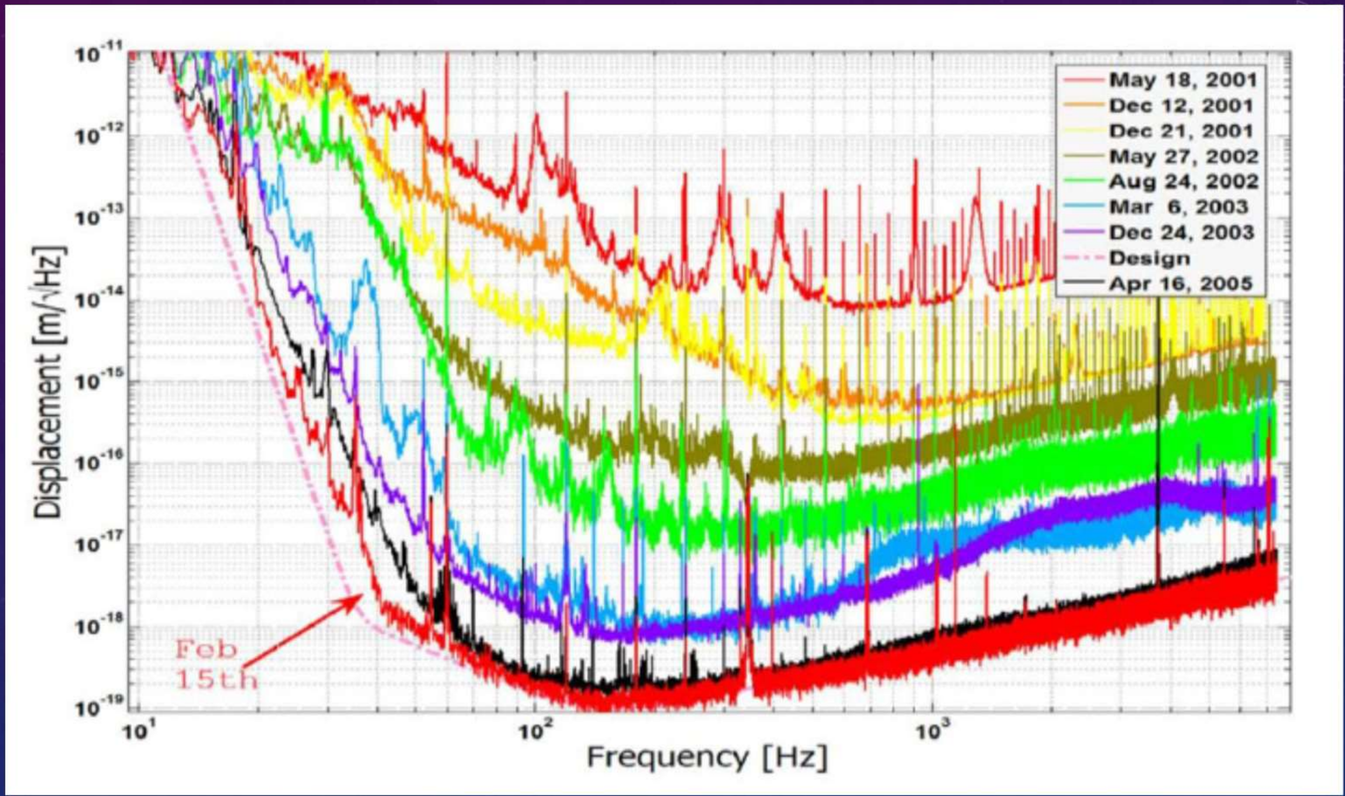


Image Credit: *https://www.ligo.org*

ADVANCED LIGO

- The basic goal of Advanced LIGO was to improve the sensitivity from Initial LIGO by at least a factor of ten over the entire frequency range of the interferometer
- It is important to note that a factor of x10 improvement in sensitivity increases the distance of search by that factor, since they are measuring an amplitude.
- It thus increases the volume of the universe searched for by a factor of x1000.
- The sensitivity to most sources is proportional to the volume we search.
- Therefore, there is a very high premium in LIGO on increasing the range of search, and consequently, they spend a good fraction of their time improving the sensitivity, rather than taking very long data runs.

Hanford, Washington

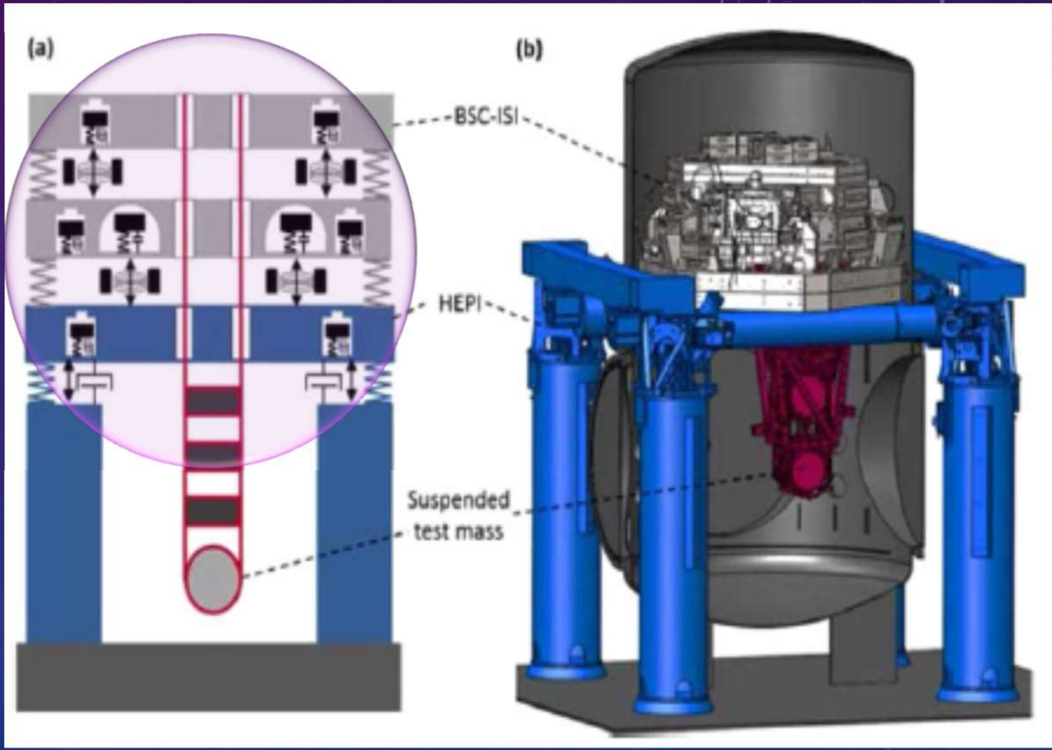
Livingston, Louisiana
Image Credit: *https://www.ligo.org*

ADVANCED LIGO INTERFEROMETER INFRASTRUCTURE

Image Credit : *https://www.ligo.org*

ADVANCED LIGO ISOLATION PROCESS

- The improved seismic isolation system uses both passive and active isolation.
- Hydraulic External Pre-Isolator(HEPI) uses forces generated by hydraulic pressure to cancel low frequency seismic noise, primarily due to forces from ground vibration.
- The Internal Seismic Isolator(ISI) is an actively controlled platform, in which each stage is supported by three Maraging steel blade springs. The vibration is sensed in six degrees of freedom and reduced by applying forces through a control feedback loop.



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SENSITIVITY OF ADVANCED LIGO

- The advanced LIGO interferometer had increased the sensitivity to almost what was predicted from theory for the setup.

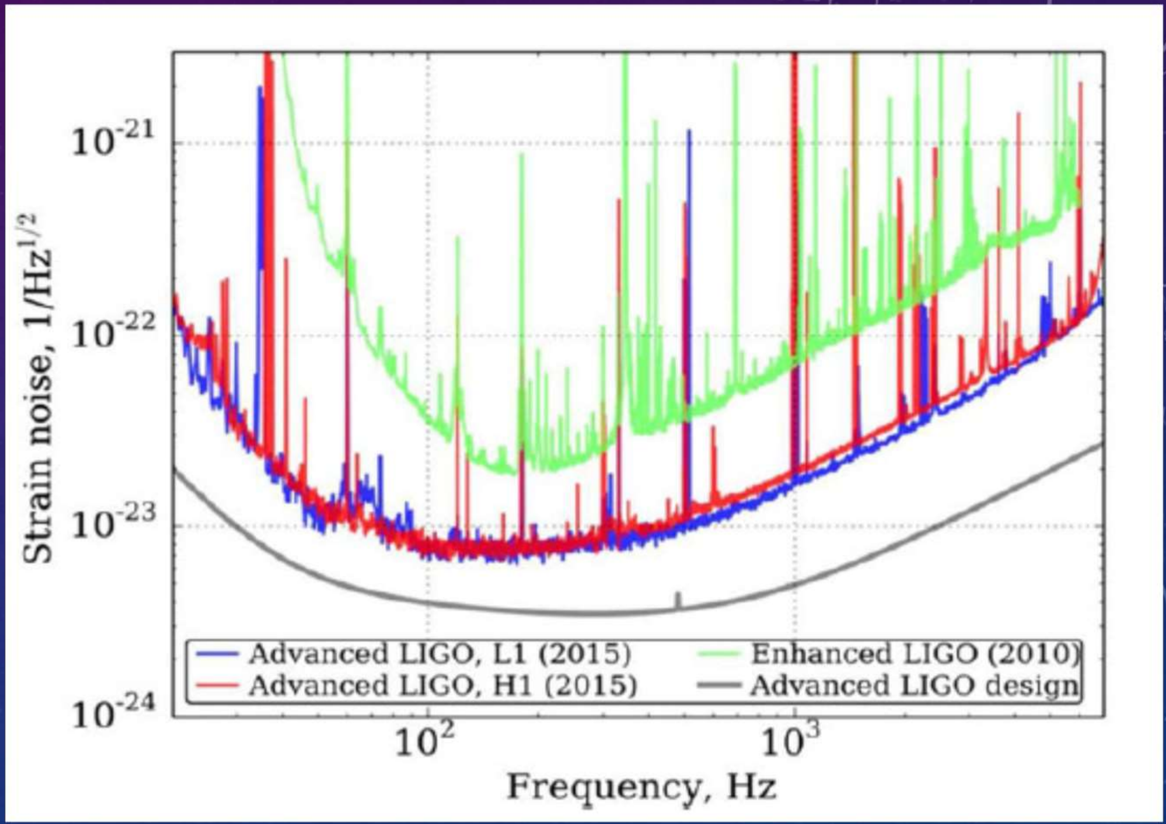

Image Credit: *https://www.ligo.org*

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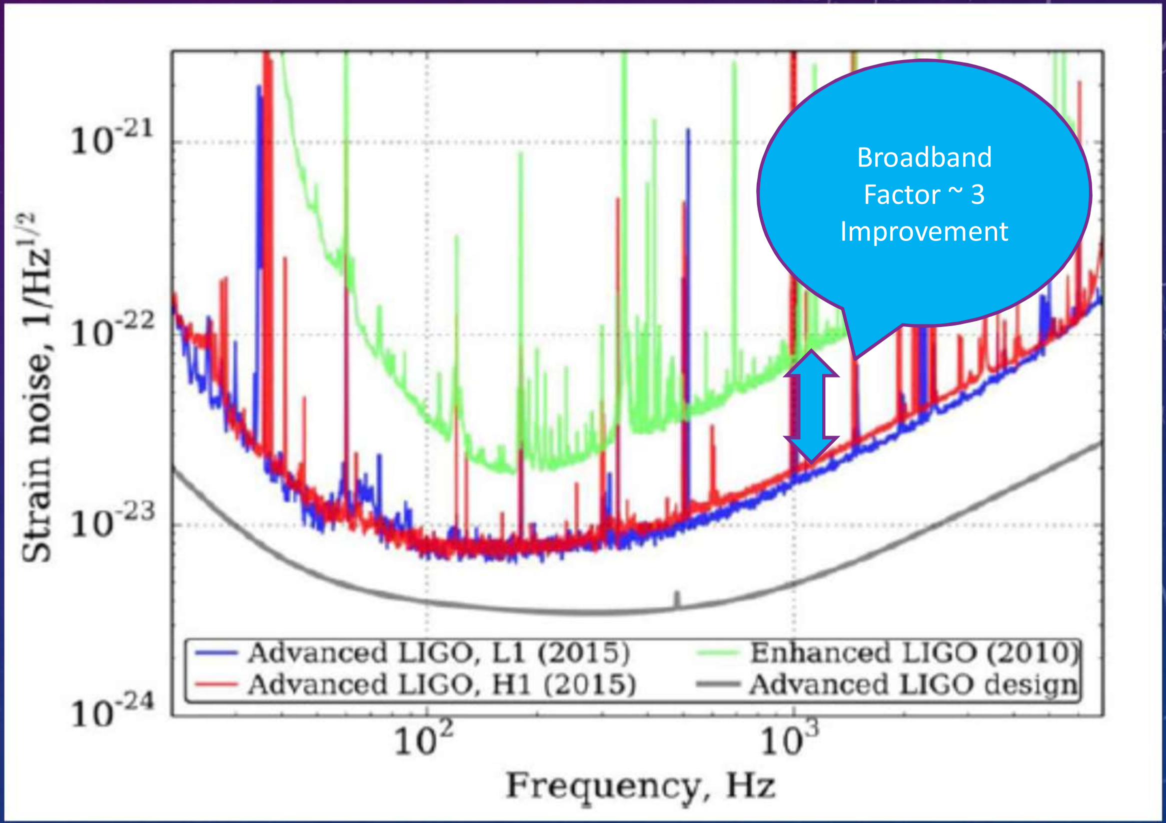
- The advanced LIGO interferometer had increased the sensitivity to almost what was predicted from theory for the setup.
- The broadband factor for the signals was increased by a factor of 3. So, the setup did the work in 1 year what would have taken 27 years using the initial LIGO setup.



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- At lower frequencies, the advanced setup made an improvement in sensitivity by a factor of ~100 which corresponds to a factor of 1 million in the entire volume.

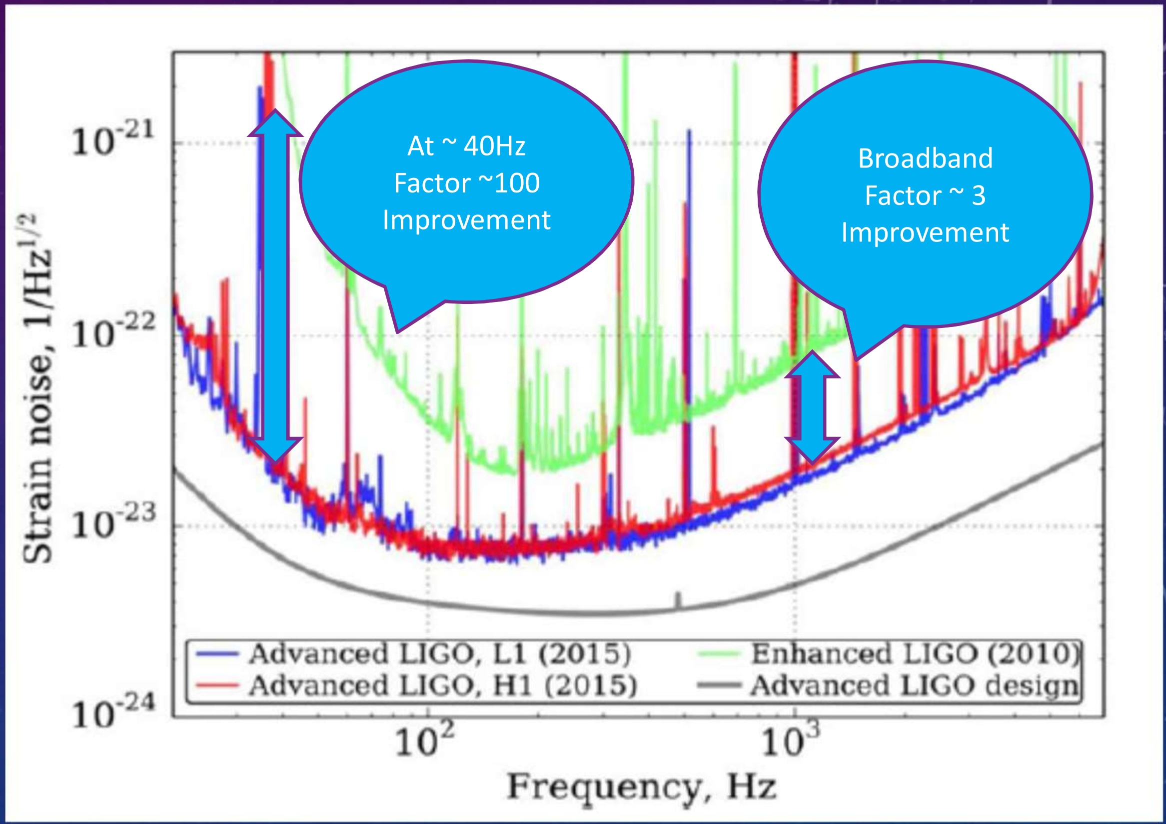


Image Credit: *https://www.ligo.org*

SEP 14, 2015

- First Gravitational Wave Event occurred twenty one years after the Initial LIGO was funded in 1994.
- It was a Binary Black Hole Merger which was named as GW150914.

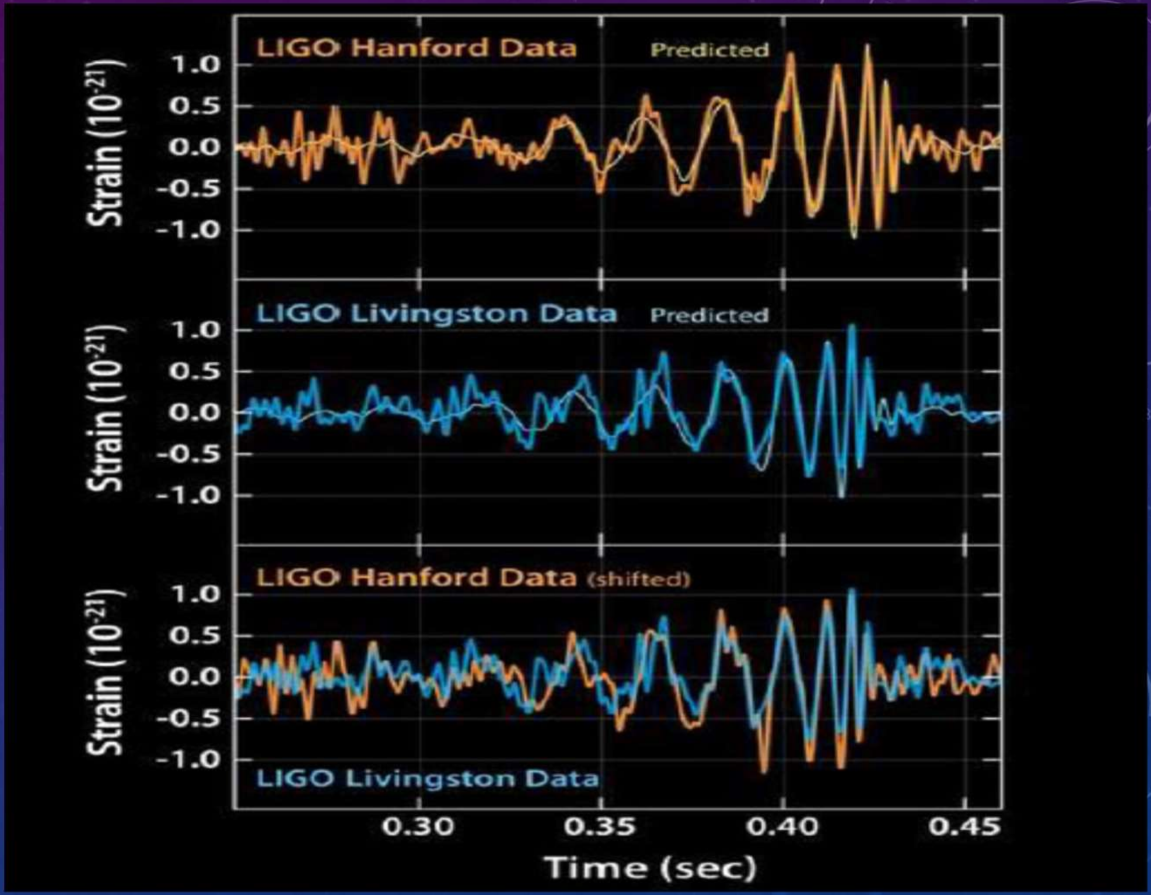


Image Credit: *https://www.ligo.org*

ANALYSIS OF THE SIGNAL

- As the objects in-spiral together, more and more gravitational waves are emitted and the frequency and amplitude of the signal increases.
- This is following by the final merger, and then, the merged single object rings down.
- The bottom pane shows on the left scale that the objects are highly relativistic and are moving at more than 0.5 the speed of light by the time of the final coalescence.
- On the right side, the scale is units of Schwarzschild radii and indicate that the objects are very compact, only a few hundred kilometers apart when they enter the frequency band.

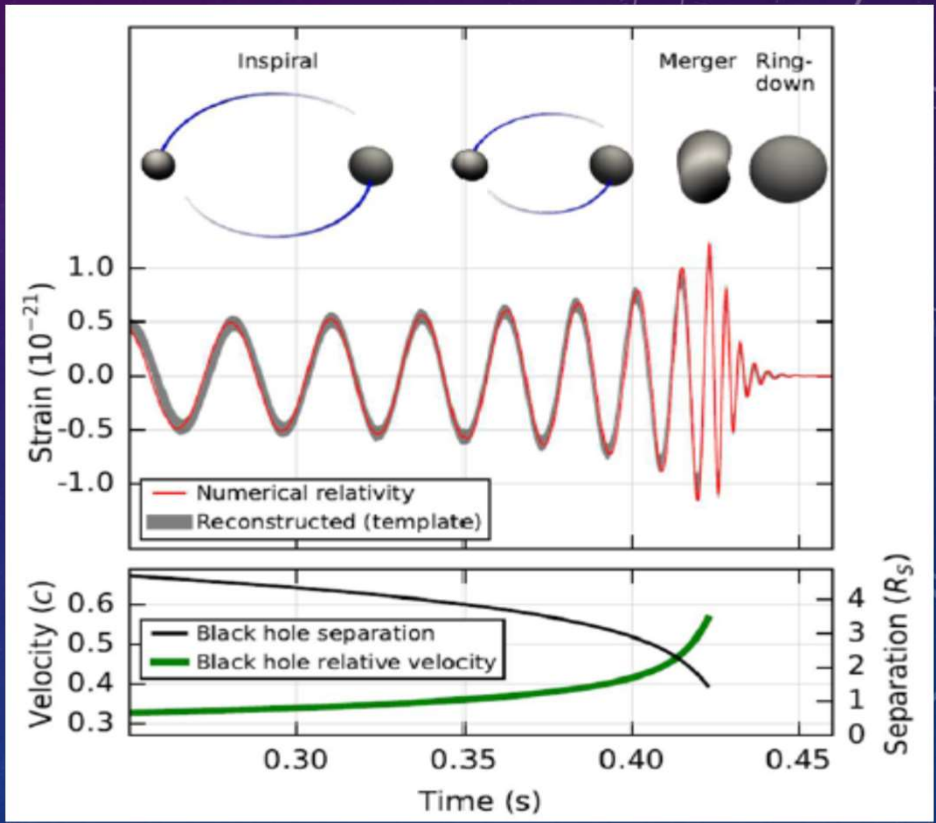
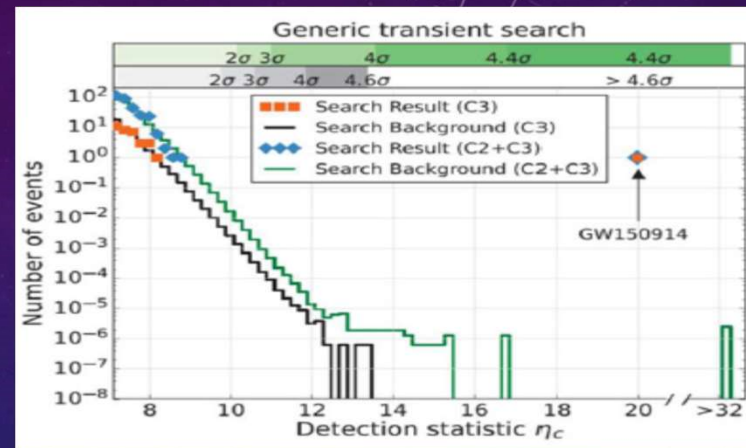


Image Credit: *https://www.ligo.org*

STATISTICAL CERTAINTY

- In order to be confident that what they observed was a real event and not a background fluctuation, they directly measured the background probability by comparing coincidence time slices for the two detectors, both in time and out of time!
- The graph shows the statistical significance for the event, compared to the measured background levels, under two different assumptions.
- The upper plot shows the event at the level of having statistical significance $\sigma > 4.6$. This plot assumes a generic signal shape for the event.
- The bottom plot shows a significance of $> 5\sigma$, when a binary coalescence form is assumed. At this early stage in LIGO, they are only declaring 5σ events as gravitational wave binary mergers.



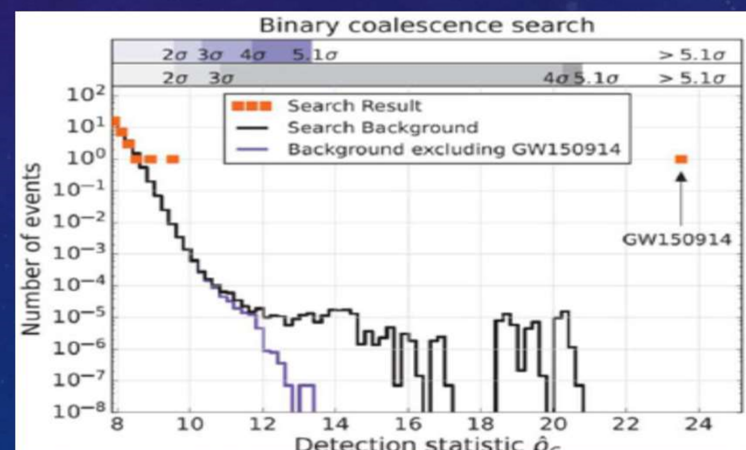


Image Credit: *https://www.ligo.org*

MORE BLACK HOLE MERGERS

- These are some more black hole merger events which were detected by Advanced LIGO and analyzed.
- Notice that the amount of time and number of cycles observable in LIGO is very dependent on the mass of the black hole system.
- The heaviest black hole that they observed was the first one and they only observed a few cycles, while for the lightest one (GW151226) they have many cycles.

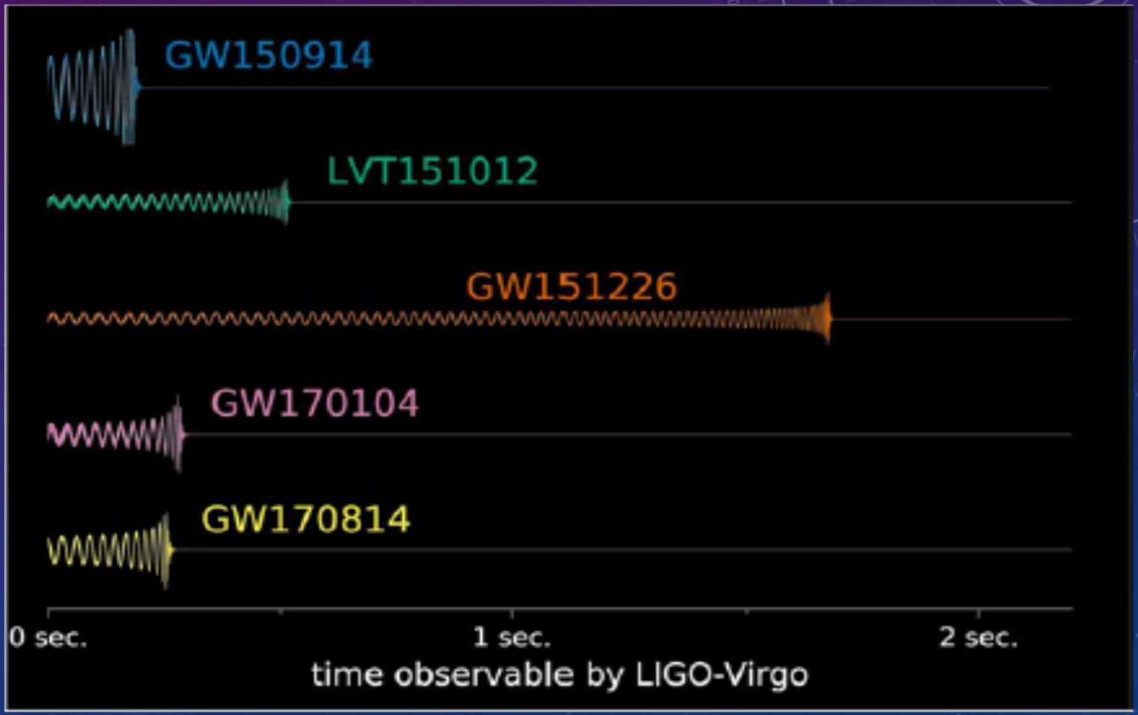


Image Credit: *https://www.ligo.org*

SCIENCE IMPLICATIONS OF OBSERVED BLACK HOLE MERGERS

Conclusions from the first observations of black hole merger observations from gravitational waves include the following:

- Stellar binary black holes exist.
- They form into binary pairs.
- They merge within the lifetime of the universe.
- Masses ($M > 20\ M_{sun}$) are considerably heavier than what was known or expected of stellar mass black holes.

FUTURE GOALS

- The next challenge will be to distinguish between these or other possibilities for the origin of such heavy stellar black holes.
- More events will give us distributions of masses and other parameters, while larger signal/noise events will enable determining the other feature of these mergers. For example, are the spins of the merging black holes aligned, anti-aligned or is there no correlation in the spins?
- Our other major scientific goal is to test general relativity in the important regime of strong field gravity. The merger of black holes presents just such a new ‘laboratory’ for these studies. We can compare the observed waveform with the predictions of general relativity looking for deviations. So far, all tests are in good agreement with the theory.

CONCLUSION

- Gravitational waves represent a completely new way to view the universe.
- We have every reason to expect that we will discover new phenomena and learn 'new' astrophysics from gravitational waves.
- This has already been realized from the very first observations of gravitational events.

1916
Einstein's prediction of Gravitational Waves

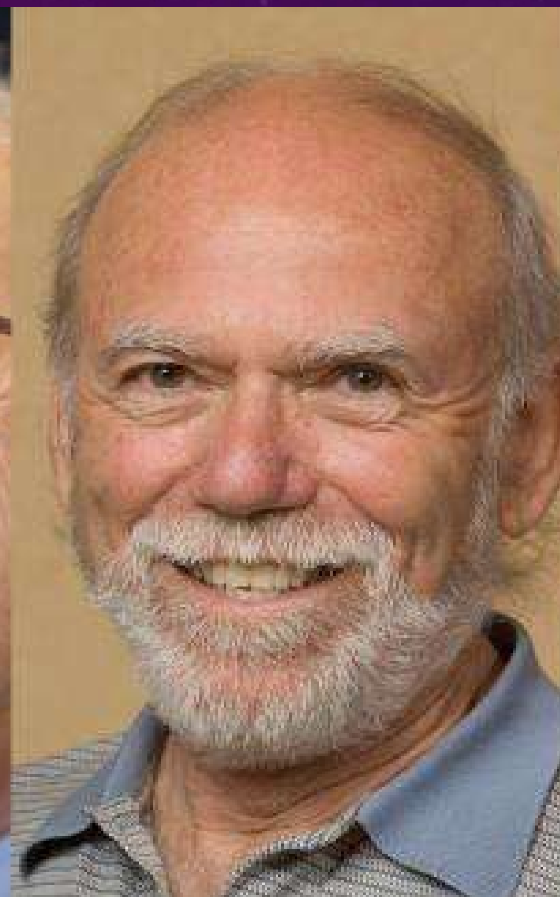
1974
Russell and Hulse discover the first evidence of a wave from a pulsar.

1994
Initial LIGO was set up with Barry Barish as their program director.

2008
Advanced LIGO was created to enhance the initial LIGO detectors.

2015
Gravitational Waves were first observed for a black hole merger event.

Rainer Weiss



Barry Barish

Kip Thorne

Thank You!!!!